curve (solid lines) has lower mechanical quality factor compared to the first-order model (dashed lines) since the model does not take into account the loss from material and package. Nonetheless, the range of measured $R_{piezo}$ agrees reasonably well with the first-order model. For each material, $R_{piezo}$ spans much of the ~2 kΩ to ~200 kΩ targeted range in the IB, suitable for IMDs. The measurement results demonstrate the utility of the series circuit model as a first-order design tool for IMD receivers.

TABLE III

Measured resonance frequencies and impedances

| | PZT4 | PZT5H | $BaTiO_3$ |
|---|---|---|---|
| $f_{sc}$ (MHz) | 0.96 | 0.82 | 1.45 |
| $R_{sc}$ (kΩ) | 2.28 | 1.74 | 4.46 |
| $f_{oc}$ (MHz) | 1.27 | 1.19 | 1.58 |
| $R_{oc}$ (kΩ) | 154 | 120 | 40.2 |

B4b) Measured PCE of Receivers

**[0078]** PCE is computed from measured open circuit AC voltage across the terminals of the receiver along with the measured impedance for a given $I_0$. Measured PCE in the IB is also plotted in FIGS. **12**A-C (dotted lines). Measurements for receivers of three different materials all present high PCE with variation across the entire IB. Similar to aperture efficiency for antenna, PCE larger than unity is possible for small resonators. As an example, even with a worst case PCE of 30%, we are still able to obtain 1 mW of time-averaged available power with less than 40% of the FDA limit (7.2 mW/mm$^2$). The PCE plots indicate that off-resonance operation can be utilized to transfer power efficiently for various $P_{load}$.

B5) Adaptive Matching to Maximize Efficiency

**[0079]** With the favorable impedance profile designed and measured in the previous sections, we now demonstrate how to operate these piezoelectric receivers efficiently for a dynamically varying $P_{load}$. The total implant efficiency, $\eta_{implant}$ from (1) is maximized by utilizing the full span of $R_{piezo}$ across the IB with capacitive-only matching networks. A truly dynamic design would implement a programmable capacitive matching network, such as switchable capacitor banks, to match the inductive reactance from the receiver at different operating frequencies. A closed-loop system with data uplink can be used to adaptively change the transmit frequency and acoustic intensity for various $P_{load}$. FIG. **13** shows a conceptual diagram of a closed-loop system with an adaptive power recovery chain.

**[0080]** Series and L matching networks, shown in FIG. **14**, can be used to increase $\eta_{implant}$. More complicated schemes can also be chosen for the same purpose. Measured characteristics of the PZT4 receiver in section B4 are used to illustrate the operation and efficiency gain of the two matching networks compared to a non-adaptive system. As seen in FIG. **14**, the receiver is represented as a Thévenin model with an open circuit root-mean-squared voltage, $V_{oc}$, equal to $\sqrt{4P_{av,ele}R_{piezo}}$. A commercial full-wave bridge rectifier is selected as an example of the power recovery circuit in the power recovery chain in FIG. **8**. Due to the nonlinearity in the power recovery circuit, a more accurate characterization of $R_{in}$ looking into the rectifier and load requires an iterative approach. Therefore, circuit simulations were performed using Keysight Advanced Design System (ADS) to obtain the optimal adaptive matching parameters at various load powers. In the simulations, output voltage is constrained to be 2 V and different load resistors are used to model different $P_{load}$. Measurements on matching networks are also performed to verify the simulation results using the same components.

B5a) Series Matching Network

**[0081]** The top part of FIG. **7** shows a series matching network, the simplest implementation of a programmable matching network. In order to maximize PME, $Z'_{piezo}$ and $R_{in}$ after the series matching network, or equivalently, $Z_{piezo}$ and $Z'_{in}$ before the matching network must be complex conjugate pairs respectively. A series matching network can be easily understood as matching $Z'_{piezo}$ to $R_{in}$. As $P_{load}$ varies, the operating frequency is selected such that $R_{piezo}$ is close to $R_{in}$. The series capacitor, $C_s$, is then configured to cancel out the remaining inductive part of the receiver, making $Z'_{piezo}$ matched to $R_{in}$. The series matching network is most effective when the range of $R_{piezo}$ in the IB is large enough to cover all possible $R_{in}$.

**[0082]** FIG. **15**A shows the simulated values of $R_{piezo}$ and $R_{in}$ for optimal impedance matching as a function of $P_{load}$ from 10 μW to 1 mW. As anticipated from (2), $R_{piezo}$ follows $R_{in}$ and moves inversely with $P_{load}$. The range of $R_{piezo}$ limits the load power for which optimal matching can be obtained. For $P_{load}$ lower than 25 μW, required $R_{in}$ becomes too large to be matched by $R_{piezo}$ in the IB of the receivers; as a result, the optimal operating frequency stays at $f_{oc}$, and the PME drops. The capacitance values used for $C_s$, also shown in FIG. **15**A, range from 1 pF to ~15 pF, which is easily achieved using on-chip capacitors for miniaturization. FIG. **15**B shows the comparison of the PME between an adaptive system with a series matching network and a non-adaptive system. PME with series matching is able to reach almost 100% because of the presence of the tuned network. For the non-adaptive case, a static resonance frequency operation (at $f_{sc}$) is assumed; its PME drops significantly at lower load powers due to mismatch.

**[0083]** The analysis so far has only considered $R_{piezo}$ and neglected the PCE, but the PCE could be taken into account since $\eta_{implant}$ is related to the product of PCE and PME by (1). FIG. **16** shows the simulated $\eta_{implant}$ of the power recovery chain including efficiency of the rectifier, $\eta_{AC\text{-}DC}$, when PCE is considered in the optimization process. Note that $\eta_{AC\text{-}DC}$ is about 80% over the entire range of load power. The result shows that co-optimizing PCE and PME together produces a higher $\eta_{implant}$ for some $P_{load}$. For the PZT4 receiver, the difference is most prominent at higher $P_{load}$, from 100 μW to 1 mW, with a boost of nearly 10 percentage points at 1 mW. Therefore, maintaining an operating frequency in a high PCE region but with a suboptimal PME can increase overall efficiency. This improvement is significant because at higher power levels, higher efficiency can reduce the required transmitted power.

B5b) L Matching Network

**[0084]** As seen in the comparison between simply maximizing PME and co-optimizing PME and PCE together, the efficiency for the co-optimized case is larger for some $P_{load}$. To decouple these two parameters, we can introduce an